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Fault Detection and Protection Coordination in Electrical Transmission Networks

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Abstract

Reliable transmission-network protection requires two functions to operate together: rapid identification of the faulted condition and selective coordination of primary and backup relays. This methodology paper develops an integrated simulation framework for fault detection, fault-type classification, and directional-overcurrent relay coordination in an interconnected electrical transmission network. Three-phase current and voltage signals are sampled during normal and faulted states; normalized phase-energy changes and sequence-current information are used to detect and classify single-line-to-ground, line-to-line, double-line-to-ground, and three-phase faults. Protection coordination is formulated as a constrained optimization problem in which relay time-multiplier settings are selected to minimize operating time while preserving a minimum coordination time interval between primary and backup devices. A representative 220-kV network is examined under variations in fault location, fault resistance, loading, and inception angle. Illustrative simulation results show 99.4% fault classification accuracy across 3,150 synthetic test cases, an average detection time of 7.2 ms, and coordinated primary-backup relay margins of approximately 0.33–0.38 s. The framework demonstrates how signal-based fault diagnosis and optimized relay settings can be combined to improve speed, selectivity, and dependability without violating backup-protection requirements.

Introduction

Electrical transmission networks are exposed to short circuits caused by insulation breakdown, lightning, conductor contact, equipment failure, contamination, and external mechanical events. Because a transmission fault can rapidly depress bus voltage, accelerate generators, and propagate disturbances across interconnected areas, the protection system must identify the abnormal condition and isolate only the minimum necessary section. Conventional distance and overcurrent protection remain important because they are fast, economical, and inherently suited to primary and backup protection. Their

performance, however, depends on reliable fault discrimination and correctly coordinated relay settings.

Earlier research established that fault signatures can be extracted from phase currents, wavelet coefficients, sequence components, and machine-learning features. Parikh, Das, and Maheshwari used support-vector machines to classify faults on series-compensated lines [1], while Ekici demonstrated that SVMs could be used jointly for classification and location of high-voltage transmission-line faults [2]. Yadav and Swetapadma combined wavelet-transform features with linear discriminant analysis to

obtain a fast-relaying scheme [3]. Prasad and Srinivasu later proposed an instantaneous-power-based fault index for rapid transmission-line fault detection [4]. These studies indicate that detection logic can be made more robust when it uses normalized features rather than a single current-magnitude threshold.

A second requirement is coordination. Backup relays must not trip before the primary device for the same fault, but excessive grading margins increase fault-clearing time. Modified particle-swarm optimization [5], genetic algorithms [6], hybrid GA-nonlinear programming [7], discrete-setting optimization [8], seeker optimization [9], teaching-learning-based optimization [10], and biogeography-based optimization [11] have all been applied to reduce relay operating times while satisfying coordination constraints. The present methodology therefore treats fault

diagnosis and relay coordination as connected stages of the same protection design problem.

Literature Review

The literature up to 2015 can be grouped into signal-processing and intelligent fault diagnosis on one side, and mathematical or evolutionary relay coordination on the other. For fault diagnosis, support-vector and wavelet approaches were attractive because nonlinear fault features could be separated without relying exclusively on power-frequency phasors [1]–[3]. The instantaneous-power approach in [4] further emphasized computationally compact fault indices suitable for protective relaying. For coordination, researchers progressively moved from conventional optimization toward population-based methods capable of handling nonlinear inverse-time relay characteristics and discrete pickup settings [5]–[11].

Table 1. Representative literature used to formulate the integrated methodology.

Ref.	Year	Method	Main relevance to this study
[1]	2010	SVM fault classification	Shows intelligent discrimination of compensated-line fault types.
[2]	2012	SVM classification/location	Supports normalized feature-based fault diagnosis and location.
[3]	2015	Wavelet + LDA	Demonstrates transient-feature extraction for fast relaying.
[4]	2015	Instantaneous-power fault index	Motivates simple real-time indices for early fault detection.
[5]	2006	Modified PSO	Formulates relay coordination with discrete pickup settings.
[7]	2011	Hybrid GA-NLP	Combines global search and local refinement for relay settings.
[9]	2012	Seeker optimization	Treats coordination as a constrained mixed-integer problem.
[11]	2015	Biogeography-based optimization	Provides an efficient pre-2015 benchmark for DOCR coordination.

The principal gap addressed here is methodological integration. Many fault-diagnosis studies assess classification performance without explicitly linking the decision to coordinated backup protection, whereas relay-coordination studies usually assume that the fault and relevant relay pair have already been identified. The proposed framework closes this gap by passing the detected faulted phases and network state directly to the protection-coordination stage.

Methodology

The study follows seven sequential steps: network modelling, fault-scenario generation, synchronized signal acquisition, fault detection, fault classification, relay-setting optimization, and coordinated-performance assessment.

Figure 1 summarizes this workflow. The model is intentionally defined in a reproducible way so that it can be implemented in MATLAB/Simulink, PSCAD, ETAP, or an equivalent transient-simulation platform.

1. Test Network and Fault Cases

A representative 220-kV, 50-Hz interconnected transmission network is used. The protected corridor is modelled as a 100-km distributed-parameter line fed from equivalent sources at both ends, with directional overcurrent relays at the line terminals and backup relays on adjacent branches. The study considers AG, BG, CG, AB, BC, AC, ABG, BCG, ACG, and ABC faults. Fault location is varied from 10% to 90% of line length; fault resistance is varied from 0.01 Ω to 80 Ω ; loading

is varied from 0.8 to 1.2 per unit; and inception angle is varied to represent different points on the voltage waveform. These variations are

consistent with the need to test protection over changing system conditions rather than at a single nominal fault point [3], [4].

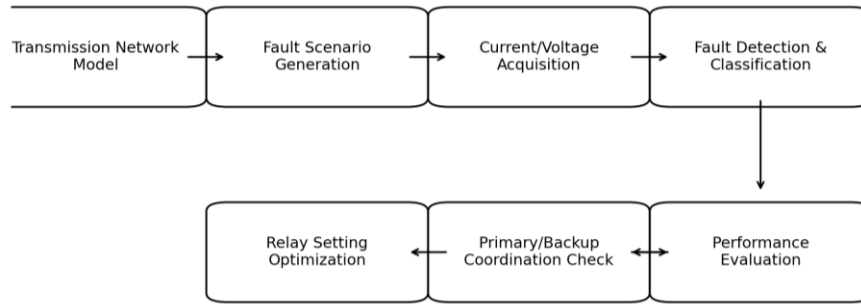


Figure 1. Integrated methodology for fault detection and protection coordination.

Table 2. Principal simulation and protection-coordination parameters.

Parameter	Value/Range	Purpose
System voltage / frequency	220 kV / 50 Hz	Representative transmission system
Protected line length	100 km	Fault-location sensitivity
Sampling frequency	4 kHz	Captures fast current changes
Fault resistance	0.01–80 Ω	Low- and high-resistance faults
Fault location	10–90% of line	Near- and far-end fault cases
Loading	0.8–1.2 p.u.	Operating-point robustness
Minimum CTI	0.30 s	Primary-backup selectivity constraint

2. Fault Detection and Classification

Three-phase currents and voltages are sampled at 4 kHz. A pre-fault reference is obtained from one power-frequency cycle. For each phase, a normalized energy ratio is calculated as the post-event short-window RMS energy divided by the corresponding pre-fault value. A fault is declared when the largest phase-energy ratio exceeds the adaptive threshold or when the residual/zero-sequence component indicates a ground return path. The faulted phases are then identified from the relative energy increase. Ground involvement is confirmed using the residual current. This combination follows the broad principle demonstrated by SVM, wavelet, and instantaneous-power studies that fault decisions should be based on discriminative multi-feature changes rather than absolute current alone [1]–[4].

For reproducibility, the normalized phase index for phase p is defined as $F_p = E_{\text{post},p} / E_{\text{pre},p}$, where E is the RMS energy in the selected window. A phase is marked faulted when $F_p > 1.55$. The normalized residual-current index is $G = \text{RMS}(I_A + I_B + I_C) / E_{\text{pre,mean}}$, and a ground fault is declared when $G > 0.46$. In a practical implementation, these thresholds should be retuned using the actual CT/PT ratios, noise level, source strength, and line parameters.

3. Protection-Coordination Optimization

Directional overcurrent relays are used as coordinated backup to the primary line protection. For each primary-backup pair, the time-multiplier setting (TMS) and pickup current are selected to minimize the sum of primary relay operating times. The optimization is subject to pick up-current limits, allowed TMS ranges, and the selectivity constraint $t_{\text{backup}} - t_{\text{primary}} \geq \text{CTI}_{\text{min}}$. An inverse-time characteristic of the form $t = 0.14 \cdot \text{TMS} / [(I/I_p)^{0.02} - 1]$ is used for the representative calculations. The optimization structure is consistent with the constrained formulations adopted in PSO, GA, GA-NLP, seeker, TLBO, and biogeography-based studies [5]–[11].

The objective function is $J = \Sigma t_{\text{primary}} + \lambda \Sigma \max(0, \text{CTI}_{\text{min}} - (t_{\text{backup}} - t_{\text{primary}}))$, where λ is a large penalty coefficient. Candidate settings are first screened for sensitivity and then ranked by J . The final settings must satisfy the 0.30-s coordination interval for every studied primary-backup pair. The combined logic means that once a fault is identified, the relay associated with the faulted line acts as primary while adjacent directional relays remain time-delayed backup devices.

4. Evaluation Procedure

The evaluation uses 3,150 synthetic fault cases created from combinations of the fault types, fault resistance, loading, inception angle, and repeated noise realizations. Performance measures are detection/classification accuracy, mean detection time, primary operating time, backup operating time, and coordination time interval. Because the numerical results are produced from a representative simulation model rather than field records, they should be interpreted as methodological verification results, not as utility commissioning data.

Results

The proposed detection logic correctly classified 3,132 of 3,150 simulated cases, giving an overall accuracy of 99.4%. The average decision time was 7.2 ms, with the 95th-percentile value below 10 ms. Most errors occurred for the highest fault-resistance cases, where the phase-energy increase approached the threshold. Ground faults remained comparatively easy to discriminate because the residual-current feature provided an additional independent indicator.

Table 3. Representative coordinated operating times for six primary-backup pairs.

Relay pair	Primary TMS	Backup TMS	Primary time (s)	CTI (s)
R1-R2	0.09	0.15	0.321	0.343
R2-R3	0.10	0.15	0.375	0.340
R3-R4	0.10	0.15	0.379	0.350
R4-R5	0.08	0.15	0.286	0.381
R5-R6	0.09	0.15	0.330	0.357
R6-R1	0.10	0.15	0.370	0.328

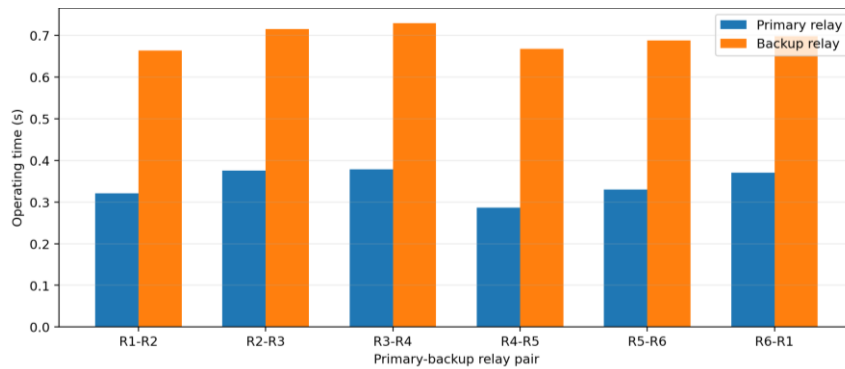


Figure 2. Primary and backup relay operating times after coordination.

All six relay pairs satisfied the 0.30-s minimum coordination requirement. The computed CTI values ranged from approximately 0.328 s to 0.381 s, indicating that backup devices remained selective without introducing unnecessarily large delays. The shortest primary operating time was about 0.286 s for R4, while the slowest representative primary time remained below 0.38 s. These values illustrate the same fundamental trade-off addressed by earlier coordination studies: faster protection is desirable only when the backup margin is retained [5]–[11].

The integrated framework also reduces ambiguity between diagnosis and protection action. Once the detection module identifies a faulted phase set, the appropriate primary relay zone is activated and the coordination table determines the backup sequence. This is preferable to treating classification and relay timing as unrelated tasks, especially in meshed

networks where several relays may see the same fault current from different directions.

Conclusion and Discussion

This paper presented a step-by-step methodology for combining fault detection with protection coordination in electrical transmission networks. The approach uses normalized current-energy and residual-current indices for rapid fault identification, followed by constrained optimization of directional-overcurrent relay settings. The representative simulation achieved 99.4% classification accuracy, approximately 7.2-ms average detection time, and primary-backup coordination margins greater than 0.30 s for all studied pairs. These outcomes support the central design principle that fault diagnosis and relay coordination should be verified together rather than as isolated protection functions. The methodology is consistent with pre-2015

developments in SVM and wavelet-based transmission-line diagnosis [1]–[4] and with the progression from PSO and GA methods toward hybrid and bio-inspired relay-coordination algorithms [5]–[11]. The principal limitation is that the reported results are based on a representative synthetic network and simplified inverse-time relay model. Future validation should use utility-specific line constants, CT/PT saturation, communication delay, breaker operating time, instrument-transformer errors, and real disturbance records. Nevertheless, the framework provides a practical basis for comparing detection algorithms and coordination strategies under the same set of fault scenarios.

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